

An Apparent Hard X-ray Decline of CH Cygni

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Abstract

CH Cygni is a symbiotic star consisting of an M giant and an accreting white dwarf, which is known to be a highly variable X-ray source with a complex, two-component, spectra. Here we report on two *Suzaku* observations of CH Cyg, taken in 2006 January and May, during which the system was seen to be in a soft X-ray bright, hard X-ray faint state. Based on the extraordinary strength of the 6.4 keV fluorescent Fe K α line, we show that the hard X-rays observed with *Suzaku* are dominated by scattering.

Key words: accretion: accretion disk; stars: binaries: symbiotic; stars: individual (CH Cyg); X-rays: star

1. Introduction

A symbiotic star is a binary composed of a red giant and a hot blue component, often an accreting white dwarf. Many symbiotic stars have been detected as soft X-ray sources using *ROSAT* (Mürset et al. 1997). The *ROSAT* detections can usually be classified into two types. One is of the supersoft type, which can be understood as photospheric emission from the hot white dwarf. The second type is optically thin plasma emission with temperatures of order 10^7 K, which Mürset et al. attributed to the colliding winds. That is, a strong, fast (~ 1000 km s $^{-1}$) wind from the vicinity of the accreting white dwarf, which, in many cases, are known to be present through studies of UV and optical emission lines, is colliding with the dense, low-velocity wind from the M giant, shock-heating the gas to X-ray emitting temperatures. More recently, a subset of symbiotic stars have been shown to be a strong source of hard (> 10 keV) X-rays in the *INTEGRAL* Galactic plane scan and in the *Swift* BAT survey (Kennea et al. 2006 and references therein), which requires the presence of yet another type of X-ray emission in these symbiotic stars.

CH Cygni is an oft-observed, yet poorly-understood symbiotic star, at a distance of 245 ± 50 pc according to the *Hipparcos* parallax measurements (Perryman et al.

1997). It has produced radio (Taylor et al. 1986) and optical (Solf 1987) jets, which appear to be ejected in the plane of the sky as seen from the Earth, implying an accretion disk and/or binary with an inclination angle of nearly 90° . Hinkle et al. (1993) analyzed a large body of infrared spectra and proposed CH Cyg to be a triple system, consisting of a 756 day period inner binary in an 14.5 yr orbit around a third component. However, Munari et al. (1996) cautioned against the triple system interpretation on several grounds. In particular, the orbital solution of Hinkle et al. requires a low inclination angle, contrary to the indications from the jet data. In addition, such a low inclination then results in the unrealistically low mass ($0.2 M_\odot$) for the white dwarf. To add to the confusion, Skopal et al. (1996) claimed that CH Cyg was a triple system as proposed by Hinkle et al. (1993) but both the inner and the outer binaries were eclipsing, thus requiring high inclination angles for both. More recently, the similarity between the 756 day period of CH Cyg with non-radial pulsations in quite a few semi-regular variables has become apparent; therefore, the 756 day period of CH Cyg is likely to be a non-radial pulsation mode rather than an orbital period (Schmidt et al. 2006 and references therein).

CH Cyg has been known to be a variable X-ray source for many years; the early X-ray data from *HEAO-1* to

EXOSAT are summarized by Leahy & Taylor (1987). It was detected with *ROSAT* showing the colliding wind-type spectrum and an additional hard component (Mürset et al. 1997). However, it was the *ASCA* observation that revealed the dramatic two-component X-ray spectrum (Ezuka et al. 1997). There is a relatively unabsorbed soft component, dominant below 2 keV, that can be modeled as two-temperature ($kT \sim 0.2, 0.7$ keV) optically thin thermal plasma emission. Above 2 keV, there is a separate, highly absorbed hotter component ($kT \sim 7$ keV). Ezuka et al. (1997) interpreted the latter as due to accretion onto a $>0.44 M_{\odot}$ white dwarf, and the former as either from the M giant or from the jets. Wheatley (2001) proposed an alternative interpretation of a single spectral component seen through an ionized wind of the M giant. A *Chandra* HETG observation was performed to decide between the two models, but CH Cyg was found to be much fainter than during the *ASCA* observation, making the grating data of little use. Instead, Galloway & Sokoloski (2004) analyzed the 0th order data and discovered a weak, spatially extended emission from the jet, in addition to the much brighter, spatially unresolved, component.

Here we report on two *Suzaku* observations of CH Cyg performed in 2006. We have also re-analyzed the *ASCA* data and the *Chandra* zeroth order data, and present the results in a uniform manner.

2. *Suzaku* Observations

We observed CH Cyg twice with the Japanese-US X-ray astronomy satellite, *Suzaku* (Mitsuda et al. 2006). The exposure times with the X-ray Imaging Spectrometer (XIS) instrument (Koyama et al. 2006) was approximately 35 ksec on both occasions. We have analyzed the data prepared using the version 0.7 pipeline (Mitsuda et al. 2006). This results in an energy scale accurate to $\pm 0.2\%$ at Fe $K\alpha$ and ± 5 eV below 1 keV (Koyama et al. 2006). Although CH Cyg is definitely detected with the PIN detector of the Hard X-ray Detector (HXD; Takahashi et al. 2006) instrument at approximately 7×10^{-12} ergs $\text{cm}^{-2} \text{s}^{-1}$ in the 12–25 keV band, this is sufficiently close to the current systematic uncertainties in the background estimation (Kokubun et al. 2006) that we have chosen to concentrate on the XIS data. We have extracted the XIS data from a 2.5 arcmin radius extraction region centered on the source, used the 2.5–5.0 arcmin annulus as the background, and generated response files taking into account the vignetting of the X-Ray Telescopes (XRT; Serlemitsos et al. 2006) and the time-variable contamination on the optical blocking filter of the XIS¹. We have combined the spectra taken with the three units (XIS0, XIS2, and XIS3) with frontside illuminated (FI) CCDs, and analyze the combined spectrum

simultaneously with that taken with XIS1 with the backside illuminated (BI) CCD. Our source extraction region contains roughly 93% of the source flux, and this is taken into account by the response file. On the other hand, it does not account for the fact that the remaining 7% of the flux is in the background region², and this has been subtracted away; we have therefore multiplied the fluxes derived from the spectral fits by 1.08 ($= 93/(93 - 7)$). The log of *Suzaku* observations can be found in Table 1, together with a summary of the *ASCA* (see Ezuka et al. 1997 for details) and *Chandra* (see Galloway & Sokoloski 2004 for details) data.

3. Results

We present the average XIS spectra of CH Cyg from the two *Suzaku* observations in Figure 1. Data for the FI chips (black) and the BI chip (blue) are shown with a model consisting of a hard ($kT \sim 10$ keV) thermal component (the mekal model in XSPEC) seen through a simple absorber (3.2 and $2.2 \times 10^{23} \text{ cm}^{-2}$ respectively, for the two observations), plus a soft component represented as a two-temperature (0.2, 0.6 keV) mekal model. We have included an interstellar absorption term that applies to both the soft and the hard components, but it is not significantly detected with *Suzaku*.

We do not consider this to be the best model; for example, two-temperature plasma is likely just a convenient representation of the soft component, while the extra absorber that the hard component goes through probably requires a complex (such as partial covering) absorber. However, the accurate characterization of the latter is hampered by the relatively narrow effective bandpass (this component is detected strongly between 3 and 10 keV, and one has to worry about the contribution of the soft component near 3 keV). As for the soft component, we have not attempted a more sophisticated fit partly because of the remaining calibration uncertainties in the amount of contamination, as well as small residual problems in gain and resolution. Of these, allowing for an extra line broadening in particular ($\sigma = 14$ eV for the 2006 Jan observation) significantly reduces the structured residuals between 0.5 and 1 keV. In addition to calibration issues, the use of such a relatively simple model better facilitates a direct comparison with the *ASCA* and *Chandra* data.

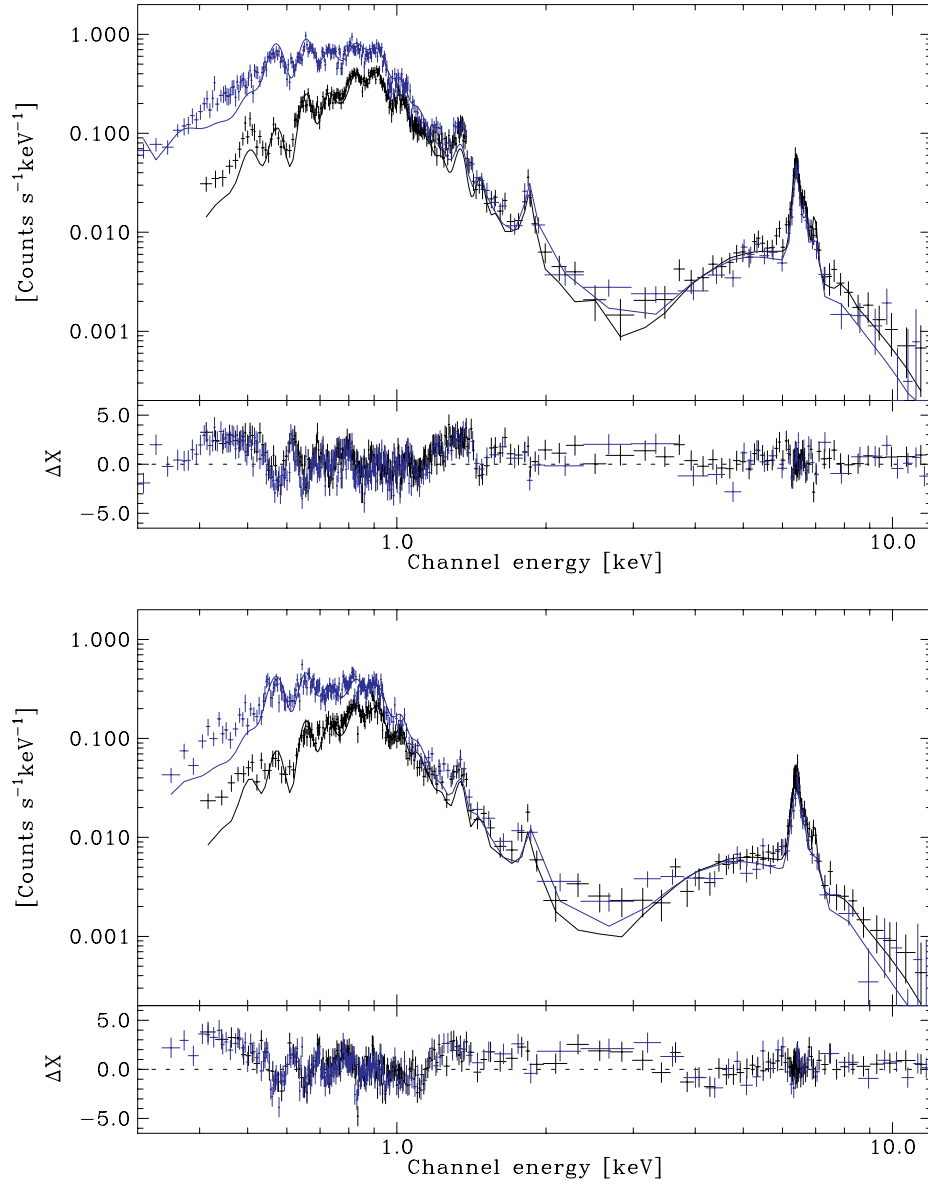
In the folded representation, these *Suzaku* spectra may look similar to the *ASCA* spectrum already published by Ezuka et al. (1997). However, it turns out that, while the soft X-ray fluxes are similar, the hard X-ray flux levels observed in the 2006 observations are much lower than that seen in 1994. In contrast, during the *Chandra* observation, both the soft and the hard components were much weaker than during the *ASCA* observations. We present the 0.4–2 keV and 3–10 keV fluxes in these 4 observations (without correcting for the strong absorption of the hard component) in Table 1 and the unfolded spectra in

¹ The calibration of the contamination layer is ongoing, and may result in slight errors particularly for the May 2006 observation, in part because the calibration is based on version 0.6 processing. We do not believe this causes a serious problem in the context of this paper.

² The fraction of photons that fall outside the 5.0 arcmin outer radius of the background region is negligibly small (Serlemitsos et al. 2006).

Table 1. Log of SSuzaku Observations.

Satellite	Sequence No.	Date of Obs.	Exposure (ksec)	0.4–2 keV flux (10^{-12} ergs cm $^{-2}$ s $^{-1}$)	3–10 keV flux (10^{-12} ergs cm $^{-2}$ s $^{-1}$)
<i>ASCA</i>	42020000	1994 Oct 19	21	3.3	63.4
<i>Chandra</i>	1904	2001 Mar 27	47	0.4	1.4
<i>Suzaku</i>	400016020	2006 Jan 04/05	35	3.8	2.1
<i>Suzaku</i>	400016030	2006 May 28/29	35	2.7	2.0

**Fig. 1.** *Suzaku* XIS spectra of CH Cyg in 2006 January (top) and in 2006 May (bottom). The observed data are shown together with a model (see text for a full description) folded through the instrument response.

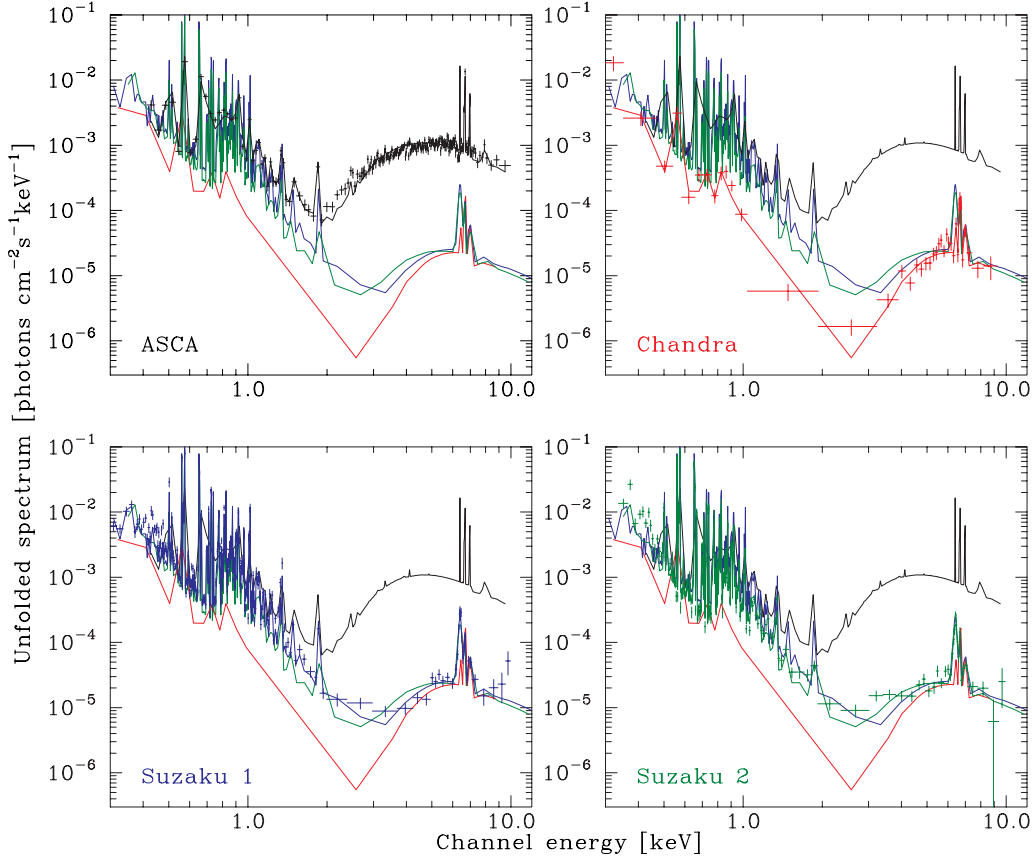


Fig. 2. Unfolded spectra from the *ASCA*, *Chandra* (red) and *Suzaku* (blue and green) observations. Each panel shows the unfolded spectrum (data and model) for one observation, as well as the best-fit model for the other three observations for ease of comparison. See text for details of the spectral model.

Figure 2 to demonstrate the dramatic changes.

A detailed study of the Fe $K\alpha$ lines (Figure 3) reveals another dramatic change. For this, we have fitted the spectra in the 5–10 keV region with an absorbed bremsstrahlung continuum plus up to three Gaussians. The center energy of the fluorescent and hydrogenic components were fixed at 6.4 and 6.97 keV, respectively, while the energy of the helium like line was allowed to float around 6.7 keV. The widths were initially set to 0, but were then allowed to vary, keeping those of the He-like and H-like lines to be identical³. Some of these restrictions are necessary for the fit to converge, but we caution that the fit results are therefore not assumption-free. Nevertheless, it is clear that the Fe $K\alpha$ complex during the *Suzaku* observations are dominated by the fluorescent line, with equivalent widths of 0.7–1.3 keV (this range representing the results of fitting the complex with slightly different models, although we cannot guarantee that we have tried all possible models). This component was not detected in the *Chandra* data, while the *ASCA* spectrum

appears to contain a more normal (Eq. W~140 eV) fluorescent line. We note that the decomposition of the complex in the *ASCA* data is not unique, and a solution without a fluorescent line is also possible. Derived parameters are summarized in Table 2.

We have also analyzed the variability of the soft and hard components. We note, however, that there is a 30–40'' level attitude wobble that is not taken into account in the current attitude solution, which may well introduce spurious variations in the light curves. We have adjusted the bin sizes for the two bands and in two observations such that, on average, each bin has 60 source counts, or a single bin signal-to-noise ratio of ~ 7.8 , and display the results in Figure 4. The hard-band light curves, particularly those of the January data, appear to be significantly more variable than the soft-band curves, showing clusters of points with correlated deviation from the mean. For example, the dip around 80,000 s and the flare-like event around 120,000 s in the January data are significantly more than the statistical fluctuation in the hard band, but are not seen in the the soft band. Overall, in 2006 January, the mean count rate in the soft band is 0.948 cts s^{-1} ; for 64 s bins, the expected statistical error is 0.122 cts s^{-1} (1σ), while the actual observed standard deviation is 0.126 cts s^{-1} . For the mean in the hard band

³ Due to the current limitations in the calibration of XIS response, we refrain from any interpretations of the apparent line width in our *Suzaku* data. In particular, the apparent broadening from the first observation to the second may be due to changes in the instrumental response that is yet to be modeled.

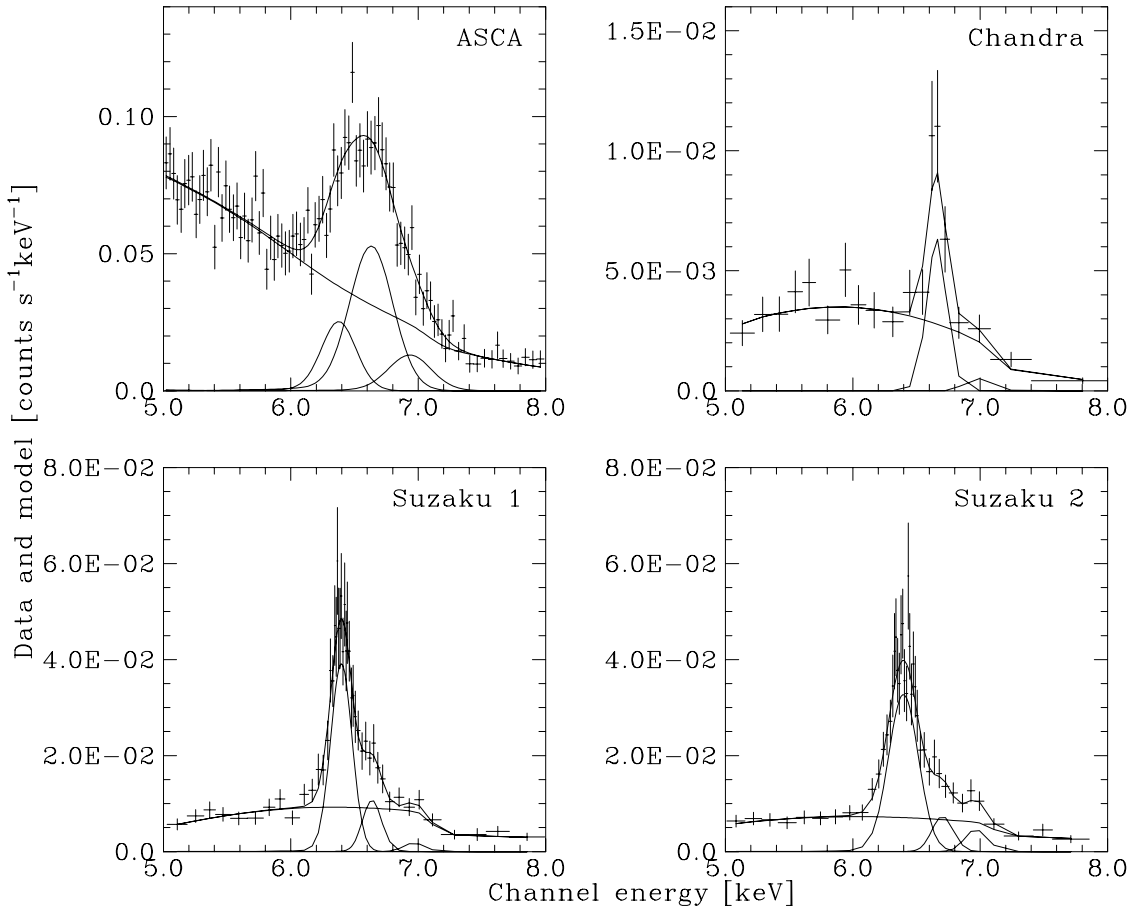


Fig. 3. The Fe $K\alpha$ profiles of CH Cyg from the 4 observations. *ASCA* SIS, *Chandra* ACIS-S (zeroth order), and *Suzaku* FI (3 units combined) data are shown with absorbed bremsstrahlung plus Gaussian fits.

is 0.170 ctss^{-1} , the statistical error is 0.022 ctss^{-1} (1σ in 360 s bins), the observed standard deviation is 0.030 ctss^{-1} . That is, the hard band light curve shows a larger scatter than expected on a purely statistical basis, while the scatter in the soft band light curve is only marginally above the expected level at most. Similarly, in 2006 May, the numbers (mean, observed standard deviation, and expected 1σ statistical error) are 0.477 , 0.0622 , and 0.610 ctss^{-1} in the soft band (128 s bin), and 0.158 , 0.026 , and 0.020 ctss^{-1} in the hard band (384 s bin). We therefore confirm that the hard component is more variable than the soft component (Ezuka et al. 1997).

The mean count rate in the soft band changed from 0.95 ctss^{-1} in 2006 January to 0.48 ctss^{-1} in 2006 May. Although the contamination build-up plays a significant role in this, the soft flux of CH Cyg does appear to have declined by roughly 30% over this period (Table 1). There is little doubt as to the reality of the longer-term variability of the soft component (Leahy & Taylor 1987; Table 1; Figure 2).

4. Discussion

CH Cyg has shown a dramatic spectral variability over the last dozen years or so, while keeping the same basic two-component structures. At the same time, *Swift* BAT 14–25 keV light curve of CH Cyg also shows a decline, from $\sim 1.0 \times 10^{-4} \text{ ctss}^{-1}$ in the 14–25 keV band during the first 3 months of 2005 to an undetectable level ($< 2.0 \times 10^{-5} \text{ ctss}^{-1}$) by the end of 2005 (Kennea et al. 2006). We first consider the nature of the hard X-ray decline from the *ASCA* era to the *Suzaku* era.

The extraordinary strength of the 6.4 keV, fluorescent Fe $K\alpha$ line shows that our direct line-of-sight is now blocked and we only observe hard X-ray photons scattered into our line of sight (Inoue 1985). The low-energy cut-offs of the hard component did not vary much among the four observations shown in Figure 2. The best-fit N_H values were 1.4 , 4.1 , 3.2 , and $2.2 \times 10^{23} \text{ cm}^{-2}$, respectively in our fits to the four observations. Such levels of absorption, which are admittedly uncertain due to the relatively simple model we have adopted, are insufficient to explain the observed equivalent widths of the 6.4 keV line in Case II of Inoue (spherically symmetric absorber, direct and scattered X-rays both observed at Earth), and requires

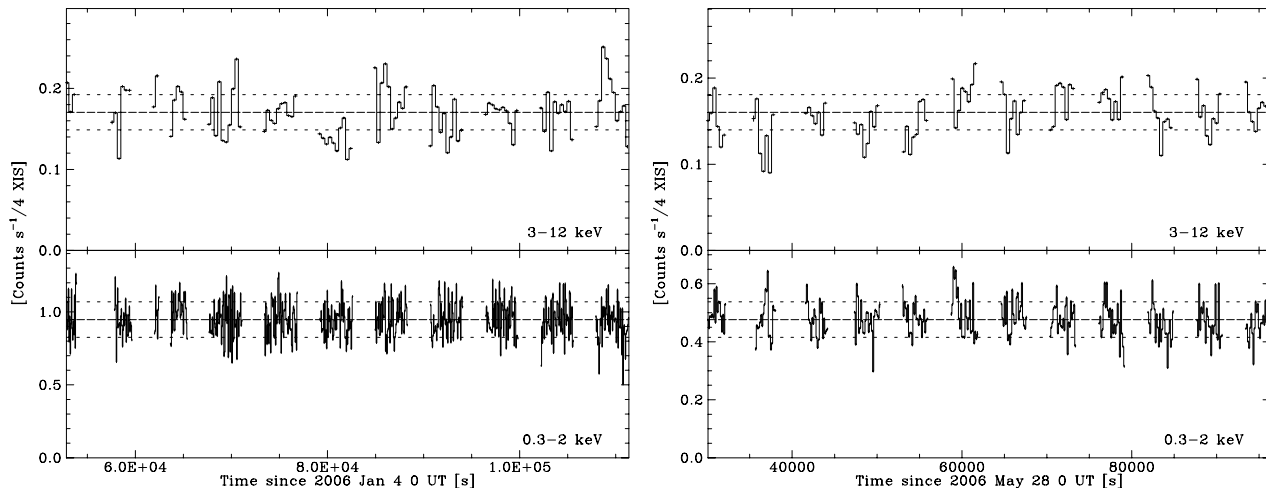


Fig. 4. *Suzaku* XIS light curves (summed count rates in all 4 XIS units) of CH Cyg in 2006 January (left) and in 2006 May (right), plotted as histograms. The bin sizes are 64 s (soft band) and 360 s (hard) for the January data, and 128 s (soft) and 384 s (hard) for the May data, resulting in 60 source counts in each bin on average. The global average and $\pm 1\sigma$ levels are indicated by dashed lines. The difference in the mean count rate in the soft band are due both to the contamination build-up and to a change in the source flux.

Table 2. Fe K α Lines of CH Cyg.

Observation	6.4 keV Eq.W. (eV)	6.7 keV Eq.W. (eV)	6.7 keV Energy (keV)	6.97 keV Eq. W (eV)
<i>ASCA</i>	140	500	6.66 (6.57–6.71)	140
<i>Chandra</i>	-	390	6.66 (6.63–6.69)	30
<i>Suzaku-1</i>	690	90	6.64 (6.60–6.68)	40
<i>Suzaku-2</i>	1150	90	6.71 (6.66–6.81)	120

Case III (direct X-rays hidden).

In contrast, the Fe K α complex was dominated by the thermal lines in the *ASCA* data, so in that observation our direct line of sight was open. The continuum flux declined by a factor of ~ 30 . In contrast, the 6.4 keV line fluxes declined from 3.5×10^{-4} photons cm $^{-2}$ s $^{-1}$ to 1.4 and 1.0×10^{-4} photons cm $^{-2}$ s $^{-1}$, respectively, in the two *Suzaku* observations. It is therefore likely that all of the direct X-rays, as well as the majority (60–70%) of the scattered X-rays, are blocked during the *Suzaku* era.

As for the central engine that produces the hard X-ray emission, we consider it likely that this is due to accretion onto the white dwarf, following Ezuka et al. (1997). In fact, the temperature (kT ~ 10 keV) and the luminosity (10^{33} erg s $^{-1}$) seen by *ASCA* are both similar to that seen in the old nova, V603 Aql (Mukai & Orio 2005). If this analogy is correct, then the X-rays are probably generated in the boundary layer between the accretion disk and a relatively massive white dwarf.

Between the M giant wind and the corona, wind, and/or jet from the accretion disk, there are more than enough candidates for the scattering medium. However, as van den Berg et al. (2006) have calculated, typical line-of-sight column through the M giant wind in a symbiotic system is $< 2 \times 10^{21}$ cm $^{-2}$, which is borne out observationally by the widespread detection of the supersoft X-rays

in symbiotic stars (Mürset et al. 1997). M giant winds are therefore far too optically thin to produce a significant amount scattered X-rays. Unless the white dwarf in CH Cyg is unusually close to the photosphere of the M giant, which now seems unlikely with the preference for a 14.5 yr orbital period (Schmidt et al. 2006), or the M giant has much stronger mass loss than in other symbiotic systems, the M giant wind is therefore unlikely to be the site of hard X-ray absorption and scattering. Moreover, the strong decrease in the 6.4 keV flux also points to a relatively compact site for the scattering, i.e., material associated with the accretion disk, such as an accretion disk corona or an accretion disk wind.

What about the Compton-thick material that is required to block out the direct hard X-rays? The M giant itself is a candidate. However, according to Skopal et al. (1996), the eclipse of the 14.5 yr binary would have happened around 2000⁴. Thus, the existing orbital solution of CH Cyg suggests that the 2006 low state is not due to an eclipse by the M giant.

We therefore consider it likely that the blockage was caused by the accretion disk. Recall that jet observations indicate a high inclination angle for the disk (Solf 1987),

⁴ In addition, the ephemeris for the 756 day “binary” indicates that the white dwarf would have been near inferior conjunction in 2006 January through May.

very close to 90° . Perhaps the disk thickness varies from epoch to epoch; perhaps the disk is slightly tilted and precesses. In either case, it seems reasonable for a highly inclined disk to be able to block our direct line-of-sight. If the scattering medium is, say, a relatively compact accretion disk corona, it is plausible for a tilted and/or thickened outer disk also to block a significant fraction of the scattered X-rays, as we have inferred from the decline in fluorescent Fe line flux.

If this picture is correct, the same thickening or precession of the accretion disk may also explain some of the optical/UV variability of CH Cyg. New optical/UV observations in the *Swift* era will enable a direct comparison of hard X-ray and optical/UV variabilities.

What can we learn about the soft component from the *Suzaku* data? We believe we now have sufficient data to disprove the ionized absorber interpretation of Wheatley (2001). First, the analysis of Ezuka et al. (1997) showed that while the hard component was significantly variable, the soft component was consistent with Poisson noise. This is difficult to explain in the ionized absorber model. Second, we do not believe that the Compton-thick material blocking our line of sight to the hard X-ray emission region can be significantly ionized, given the modest X-ray luminosity (of order 10^{33} ergs s $^{-1}$) of CH Cyg. Finally, the He-like line of Mg is clearly seen in Figure 1, while the H-like line is not. Since the latter is stronger in any plasma hotter than $kT \sim 0.8$ keV, we conclude that the soft component is dominated by plasma cooler than $kT \sim 0.8$ keV. This is also consistent with the strengths of other emission lines (O, Fe L, Ne) seen below 1 keV, which would be significantly diluted if much hotter plasma co-existed in the emission region.

We therefore conclude that the soft X-rays indeed are a distinct component. The emitting region must be separate from, or significantly more extended than, the hard X-ray emitting region. On the other hand, the bulk of the soft X-rays were spatially unresolved with *Chandra* (Galloway & Sokoloski 2004). This sets the maximum size to be of order 100 AU ($0.4''$ at 250 pc), or 800 light minute in radius. The entire binary is likely to be smaller than this, assuming a 14.5 yr orbital period. An extended emission region, comparable to the size of the binary, is expected in the colliding wind interpretation, in which the M giant wind is colliding with an outflow from the vicinity of the accreting white dwarf. The exact nature of the latter is unclear; it can be a compact jet (unlike that produced the spatially-resolved X-rays observed with *Chandra*; Galloway & Sokoloski 2004), or it can be a less collimated outflow, more appropriately termed wind. Colliding wind systems are usually not highly variable on short time scales, presumably because any local instabilities are averaged over the large emission site. Only a global change (changes in binary separation or in the wind mass loss rate) can modulate the X-ray flux significantly. If the colliding wind emission is from a 10 AU size region, and the accretion disk wind velocity is $1,000$ km s $^{-1}$, then we do not expect significant modulation in soft X-rays on time scales shorter than about 2 weeks from a “wind travel

time” argument. This consistent with the lack of soft X-ray variability seen with *ASCA* (Ezuka et al. 1997).

Ezuka et al. (1997) considered the soft component to be from the corona of the M giant. However, M giants are in the “coronal graveyard” to the upper right of the dividing line in the HR diagram. *Chandra* observations of single giants in this region show that coronal emissions are far too low a level to explain the soft component of CH Cyg: Arcturus is detected at 3σ level at a 0.2–2 keV luminosity of $\sim 1.5 \times 10^{25}$ ergs s $^{-1}$ and the upper limit for Aldebaran is 7×10^{25} (Ayres et al. 2003); the M supergiant Betelgeuse has a *Chandra* upper limit of $\sim 10^{28}$ ergs s $^{-1}$ for coronal temperature $> 10^6$ K (Posson-Brown et al. 2006). Whenever M giants are detected in X-rays, they are usually interpreted as due to a binary companion (van den Berg et al. 2006 and references therein). Although binarity can affect the X-ray luminosity, this is limited to short period systems (periods of 2 days – 2 weeks for RS CVn systems, for example) where tidal torque would lead to synchronous rotation, which is unlikely in a symbiotic binary. For the coronal model of the soft X-ray emission to succeed, the mass donor in the CH Cyg system must be a truly exceptional M giant.

So far, we have concentrated on the comparison between *ASCA* and *Suzaku* data. What about the *Chandra* observation, during which both the soft and the hard X-ray components were fainter and there was no detection of the fluorescent Fe $K\alpha$ line? For this, we must invoke a separate mechanism. If the accretion rate onto the white dwarf declines dramatically, we expect both the hard and the soft X-ray luminosities to drop, and this appears to be what happened in 2001.

5. Conclusions

Our two *Suzaku* observations of CH Cyg have caught the system in a soft X-ray bright, hard X-ray dim state. Based on the Fe $K\alpha$ spectra, we believe we currently observe only the scattered hard X-ray component. The decline in the hard X-ray flux is only an apparent decline, and the intrinsic X-ray luminosity of CH Cyg may still be as high as during the *ASCA* observation, though the actual value is unknowable.

A symbiotic star such as CH Cyg is filled with possible scattering media, but we favor material above the accretion disk as the scattering site. As for the object that blocks our direct view of the hard X-ray emission, we believe it is more likely to be an edge-on accretion disk than the M giant mass donor. The hard X-rays presumably originate from accretion onto the white dwarf, but further progress would require high-quality X-ray spectroscopy when the direct view is not blocked.

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